Combinatorial Measurements of PV Aging

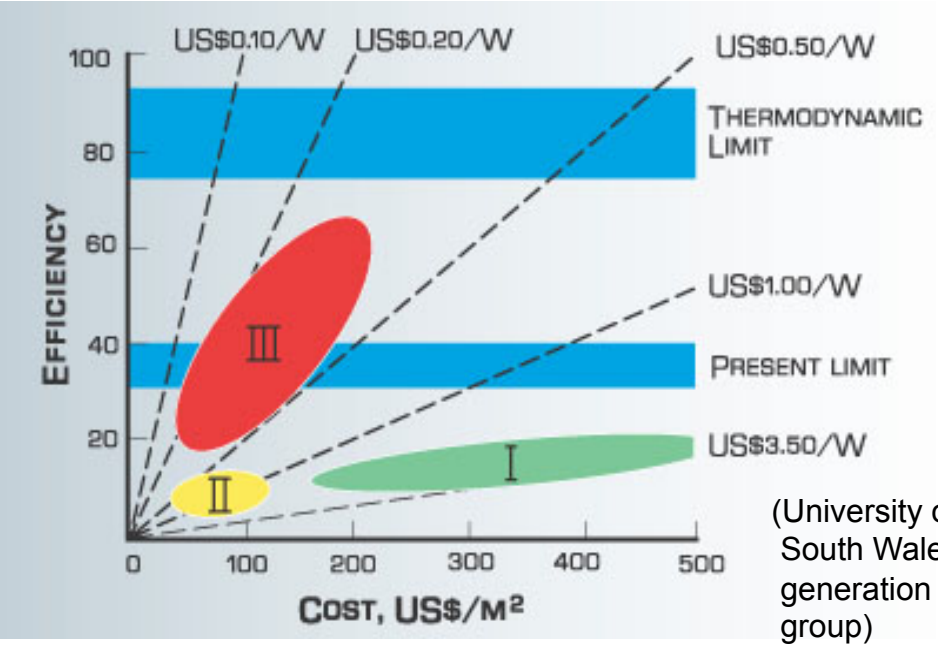
Matthew O. Reese

National Renewable Energy Laboratory (NREL)

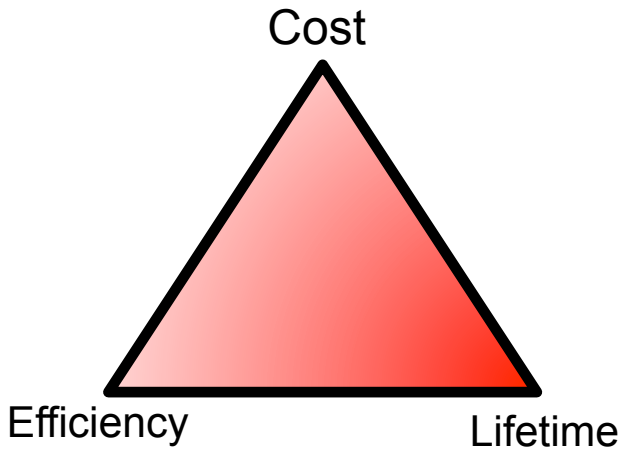
Introduction

- Organic photovoltaics (OPV) overview
- OPV efforts at NREL
- Examples of causes of instability
- Combinatorial degradation system

Motivation for Organic Photovoltaics (OPV)



(University of New South Wales 3rd generation PV group)



OPV: Solution processibility ⟶ Low cost

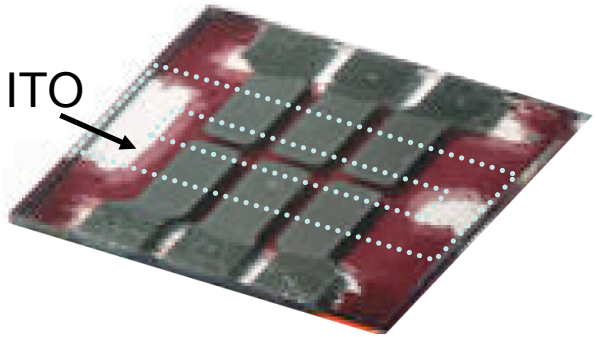
Commercial — Applied — Basic

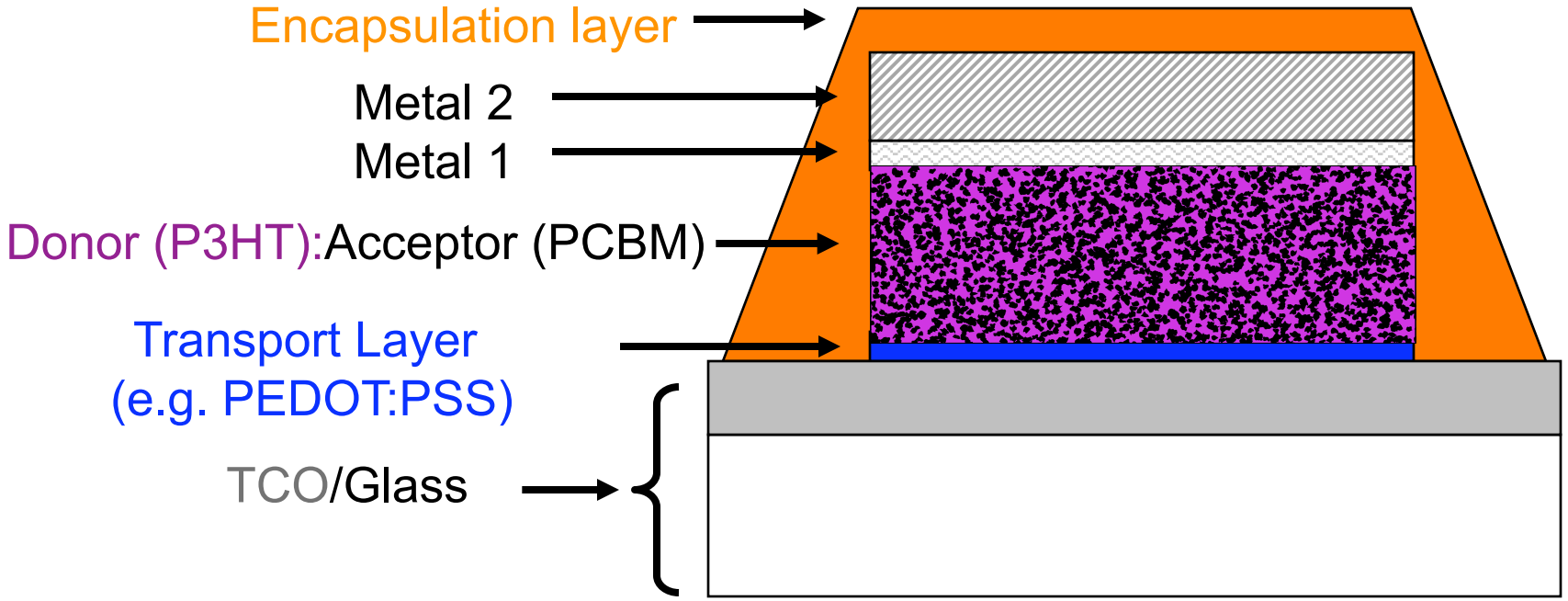
Teaming/ Collaboration

Device Fabrication & Characterization

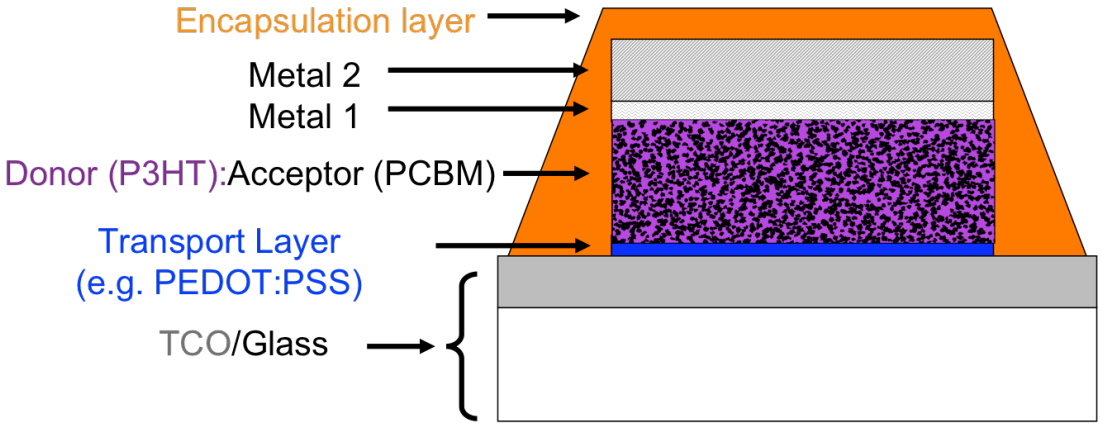
Photoinduced Electron Transfer

Typical OPV Device Geometry





OPV Kinetic Pathways



D → $h\nu$ → **D***

D* ⇄ *diffusion* ⇄ **D* + A** ⇌ **(D A)*** ⇌ **$D^{\delta+}$ $A^{\delta-}$**

At interface

D* → k_{NR} → **D + hν** (luminescence or fluorescence)

D* → k_R → **D + ΔH** (quenching)

Forward electron transfer rate: 45 fs†
Backward electron transfer rate: ~1 μs

$D^{\delta+}$ $A^{\delta-}$ → *charge separation* → **D^+ + A^-**

D^+ → *transport*

A^- → *transport*

OPV Specific Efforts at NREL

Materials
- Polymers
- Conjugated dendrimers
- ZnO
- TiO_2
- (any oxide!)
- Carbon nanotubes

Device Architecture
- Organic bulk heterojunctions
- Oxide/organic hybrid
- Inverted devices

Fabrication
- Spin coating†
- Evaporation†
- Spray deposition
- Inkjet printing†
- Ultrasonic spray†
- Dip coating
- Drop casting†

Device Measurement
- J-V†
- Certified efficiency measurements
- Impedance spectroscopy†
- EQE†

Theory

Synthesis/Characterization
- Gel permeation chromatography
- Thermogravimetric analysis
- Differential scanning calorimetry

Optical
- UV-Vis†
- TA
- PL
- TRPL
- Ellipsometry

Physical
- XRD
- NMR
- SEM
- TEM
- AFM
- Profilometry

Carrier Dynamics
- Time of flight (TOF)
- Time-resolved microwave conductivity (TRMC)†
- Time-resolved THz spectroscopy (TRTS)
- Charge extraction under linearly increasing voltage (CELIV)

† Available in a Controlled Atmosphere

International Summit on OPV Stability

- Sponsored by DOE, NREL, and Plextronics
- Focus international efforts on OPV stability
- 21 organizations, industrial/national lab emphasis
- Resulted in recommended practices for:
  - Shelf-life measurements
  - Outdoor testing
  - Indoor accelerated light soaking
  - Packaging/encapsulation testing
  - Determination of “stabilized efficiency”
- NREL organizing round robin
- Wiki: http://www.wikispaces.com/opvlifetime

Round Robin For Standardization Strategy

- First round robin send out filtered Si solar cell
  - Hamamatsu can build a set of “identical” devices
  - Soliciting international participants with a 30 lab limit
- Next - Have a device for P3HT and for Low Band Gap, CuPc/C60
  - Geometry constraints could be a problem
- Starting process now
  - January 1 to send out devices
  - Measurements to be completed in 6 months (published in journal)
  - Labs’ measurements received before sharing certified performance
- Second round
  - Better defined in ~1 year
  - Will use an OPV device from commercial supplier (Konarka has volunteered).
- Participants will be identified, but not their data
- Paper for original state of the measurements and a second for the evolution of the measurements

Proposed Roadmap Changes

Basic Standards for Device Certification

- **IEC 61646** Edition 2.0 2008-05 **Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type**
- **Designation: E 2236 – 05a Standard Test Methods for Measurement of Electrical Performance and Spectral Response of Nonconcentrator Multijunction Photovoltaic Cells and Modules**
- **Designation: E 1036 – 02 (Reapproved 2007) Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells**
- **Designation: E 1171 – 04 Standard Test Methods for Photovoltaic Modules in Cyclic Temperature and Humidity Environments**

OPV Goals

- Efficiency Goals
  - 2009 – 6.5%
  - 2020 – 14%
- Stability Goals
  - 2009 – 5% with 2000 hours
  - 2012 – 7 % with 5000 hours
  - 2020 – 10 % with 10000 hours
- Scalability
  - 2009 – 1 cm^2 with 5%
  - 2012 – 100 cm^2 with 7%

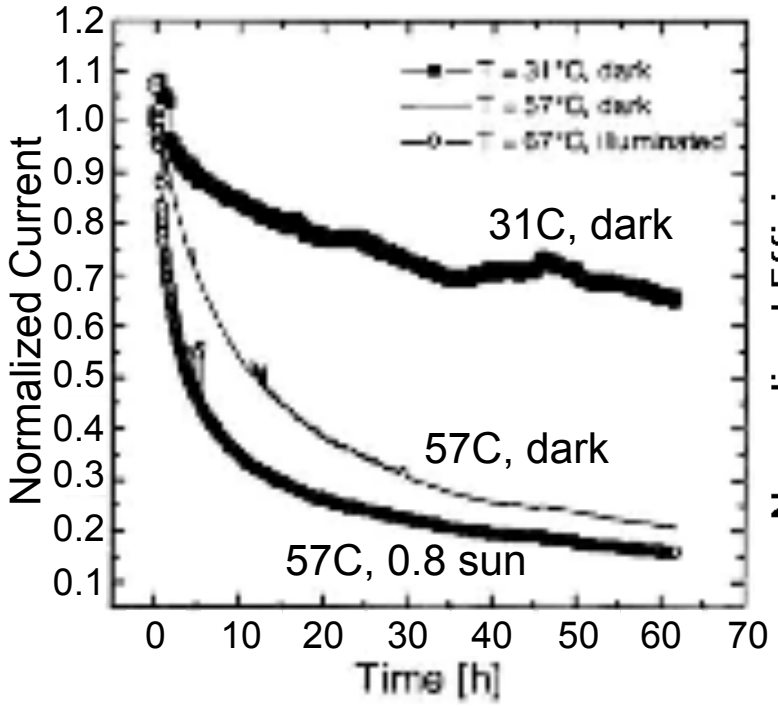
Some Causes of Instabilities

- Active Layer
- Hole Transport Layer
- Electrode Contacts: Metals, TCOs
- Interfaces
- Photo-activated mechanisms
- Temperature activated mechanisms

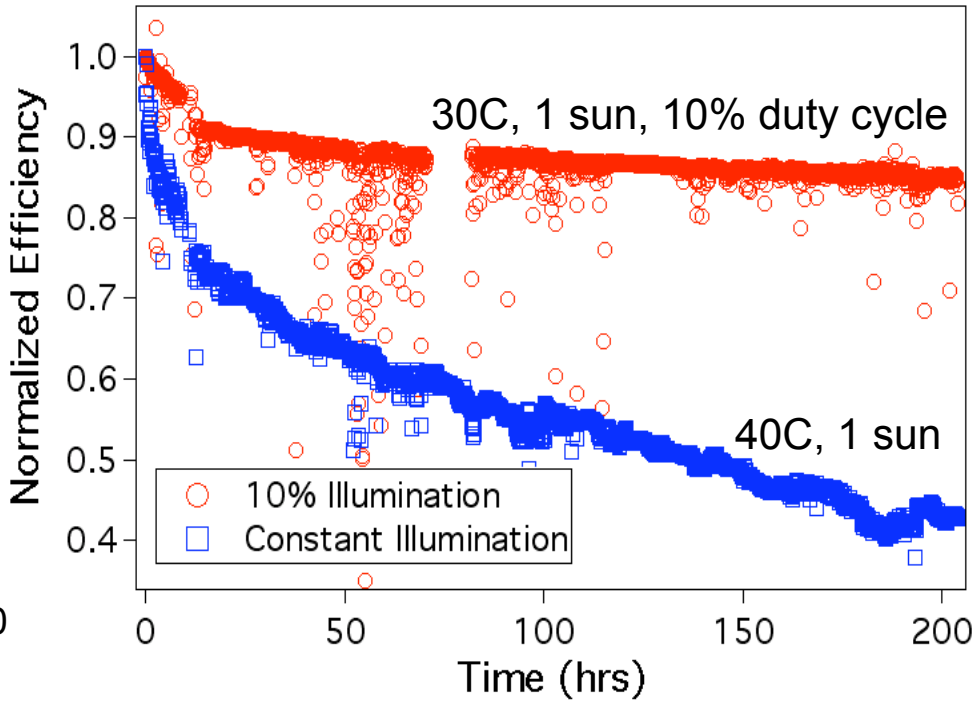
Causes of Instabilities – Active Layer

Inert atmosphere – Different Temperature, Illumination

MDMO-PPV:PCBM[1]



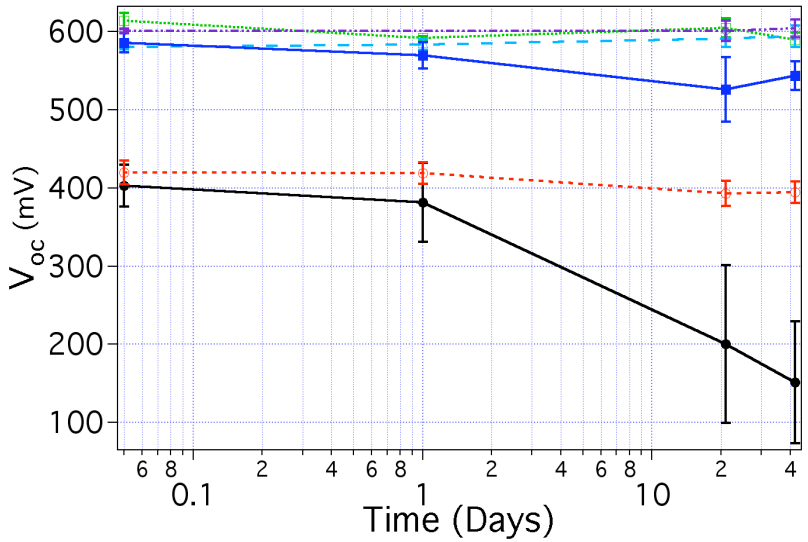
P3HT:PCBM[2]

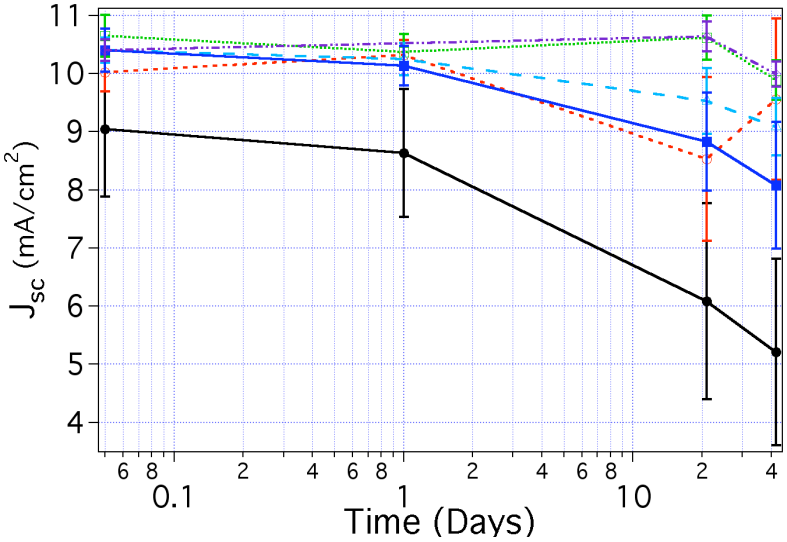


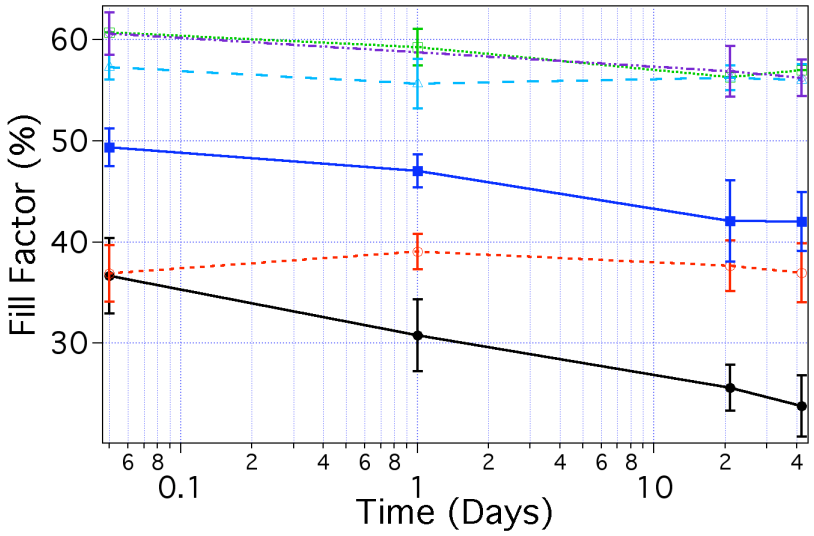
1) F. Padinger, *et al.*, Syn. Metals 121 (2001) 1605.
2) M.O. Reese, *et al.*, Sol. Energy Mater. Sol. Cells 92 (2008) 746.

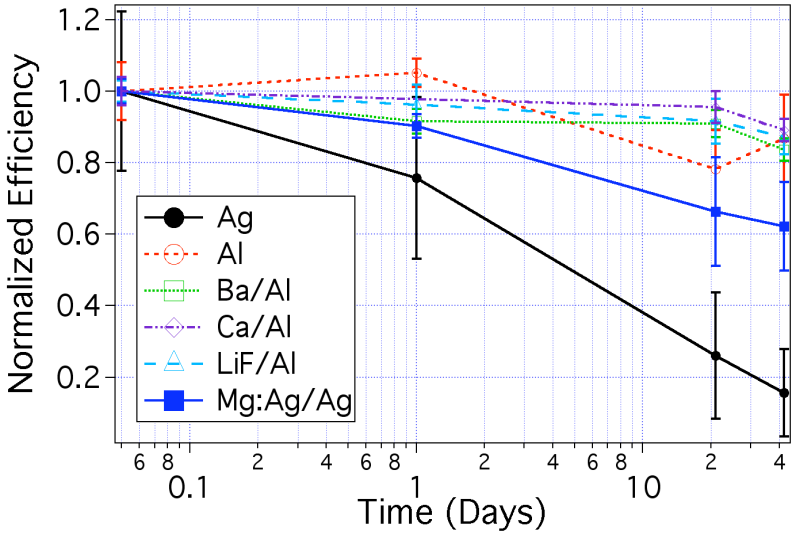
Electrode Type Study on P3HT:PCBM Devices

(Six week shelf life study)









1. M.O. Reese, *et al.*, Appl. Phys. Lett. 92 (2008) 053307.
2. M.O. Reese, *et al.*, Sol. Energy Mater. Sol. Cells 92 (2008) 746.

Building a Combinatorial Degradation Setup

- Large area light source
- Addressable filtering
- Variable load conditions
- Temperature control
- Measurement electronics
- Atmospheric control
- Modular

Solar Simulators

Elements of IEC 60904-9, ed. 2.0

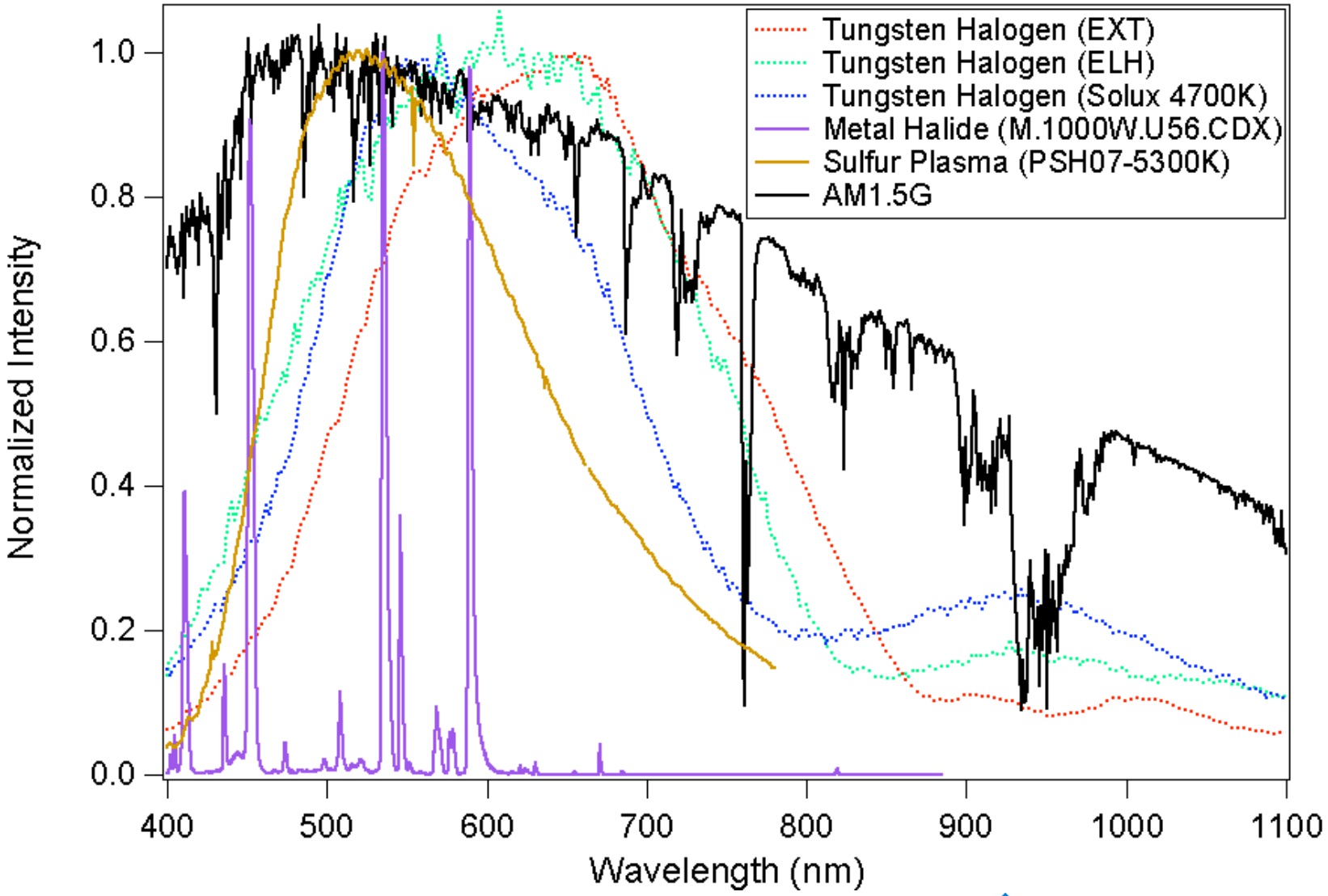
Wavelength Range (nm)	400-500	500-600	600-700	700-800	800-900	900-1100
Percent Total Irradiance from 400-100nm	18.4%	19.9%	18.4%	14.9%	12.5%	15.9%

Class	Spectral Mismatch to All Intervals	Spatial Non-uniformity	Temporal Instability	
			Short Term (STI)	Long Term (LTI)
A	0.75-1.25	2%	0.5%	2%
B	0.6-1.4	5%	2%	5%
C	0.4-2.0	10%	10%	10%

Lamps

Lamp	"Typical" Lifetime (hr)	Cost Entry (Maintenance)	Watts	Area at 1 Sun	Color Temp.	Comments
Tungsten Halogen [ELH (36-42°)]	35	<$20 (<$10)	300	~5 cm^2	3350K	Short life limits utility for lifetime studies
Tungsten Halogen [EXT (15°)]	4000-6000	<$20 (<$10)	50	~1 cm^2	3050K	May be able to make arrays (diffuser?)
Tungsten Halogen [Solux (10°)]	3000	<$20 (<$10)	50	<1 cm^2	4700K	May be able to make arrays (diffuser?)
Metal Halide [M.1000W.U56.CDX]	9000	$350-450 (~$100)	1000	~0.1 m^2		Not continuous spectrum
Sulphur Plasma [PSH07 (90°)]	15000-20000	$1000-1500 (~$200)	750	~0.1 m^2	2000-7500K	Higher power may become available
Xenon [PE240E-13FM]	1000	$13000 (~$3-4k)	2400	~0.25-0.33 m^2	~6000K	Mounting direction can be critical; rotate bubble lamps as they blacken

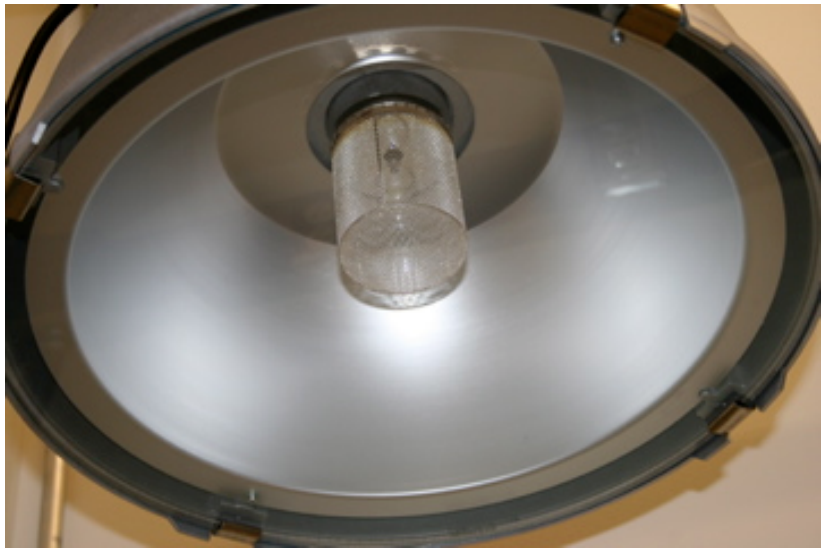
Lamp Spectra

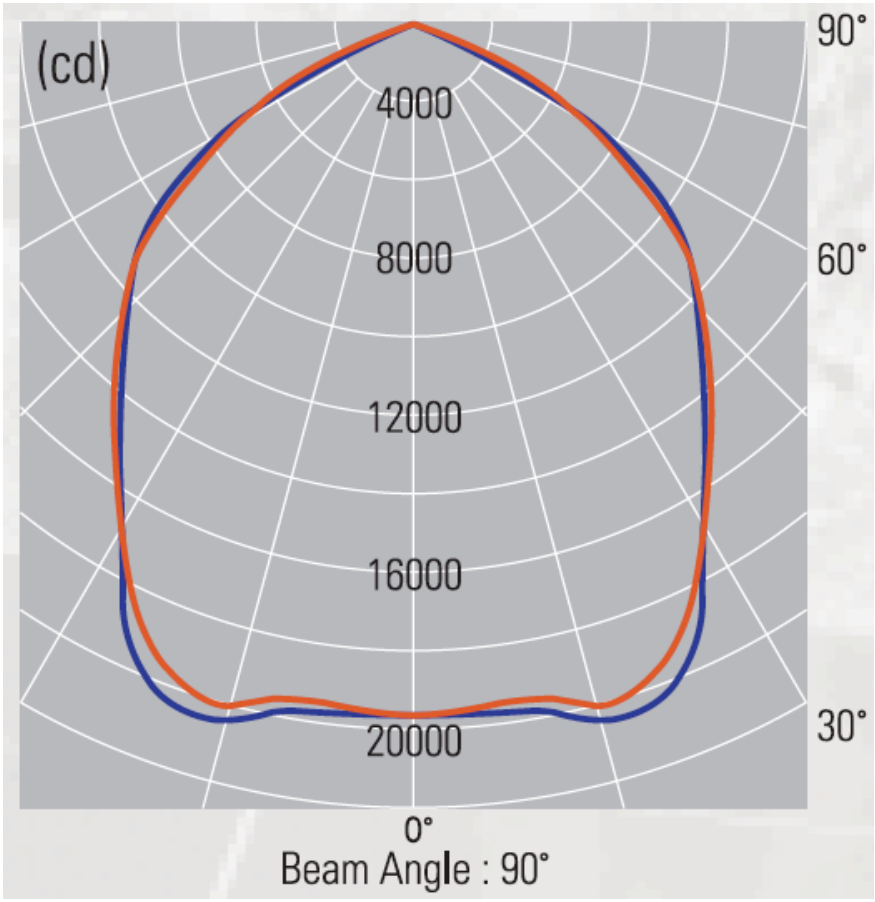


Sulfur Plasma Lamp (LG PSH07)

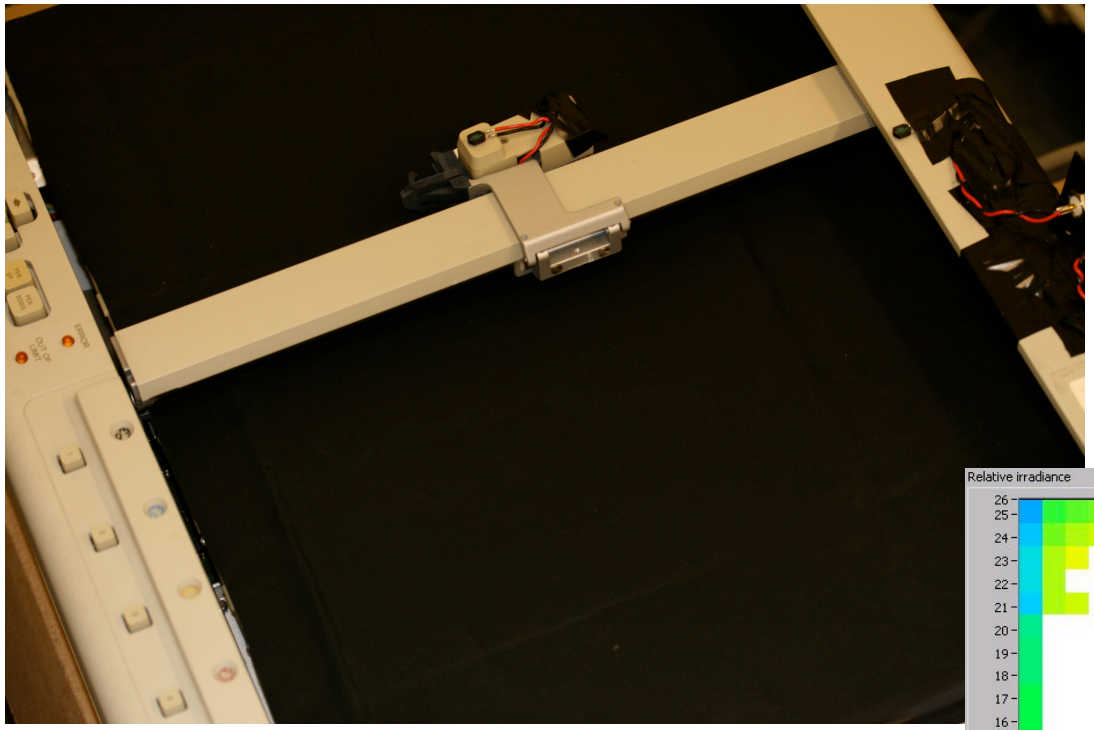
Sulfur Plasma Lamp (LG PSH07)

- Bulb lifetime 4-12 yrs
- Magnetron (power supply) lifetime 15k-20k hrs
  (1yr = 8760 hrs)
- Mismatch to P3HT:PCBM ~ 1.005
- Spatial uniformity ~ 1.5% in ±20° cone

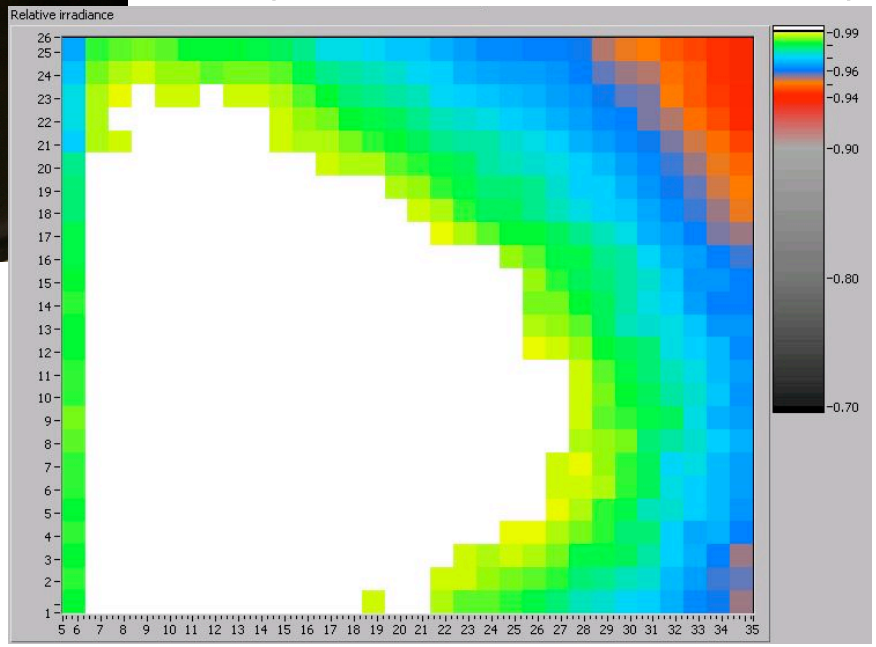




Spatial Uniformity Mapping



X25 (Cert. & Meas. Simulator)

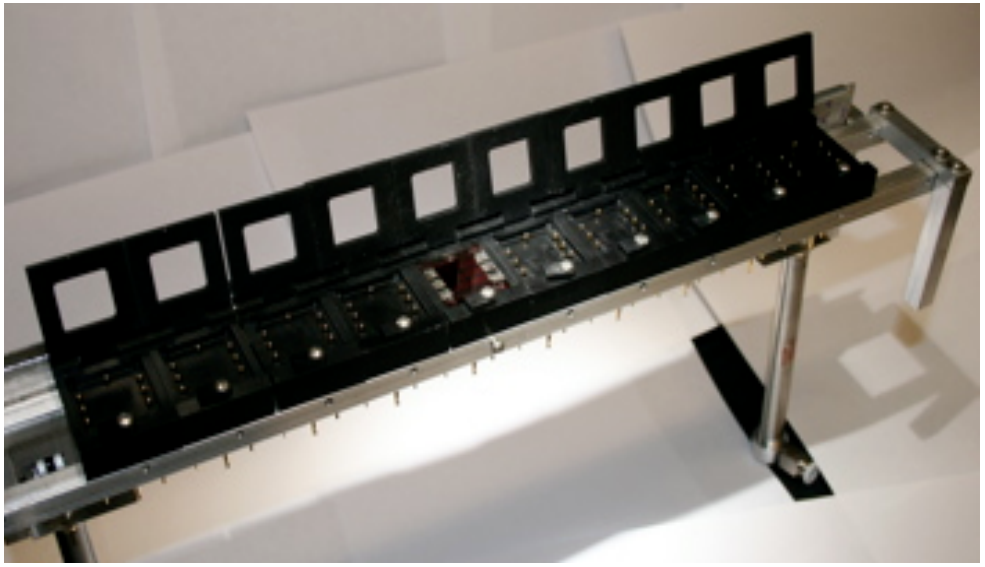


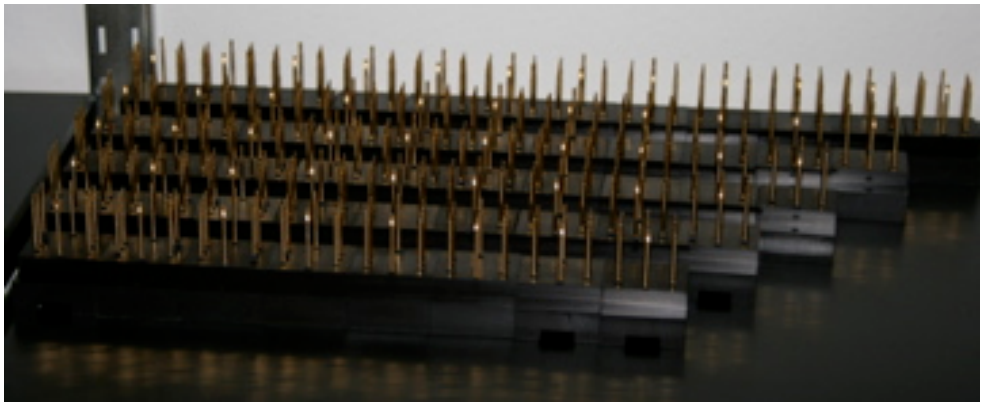
Method and example code courtesy of Dr. Keith Emery and Dr. Tom Moriarty

Combinatorial Degradation Fixturing Pieces

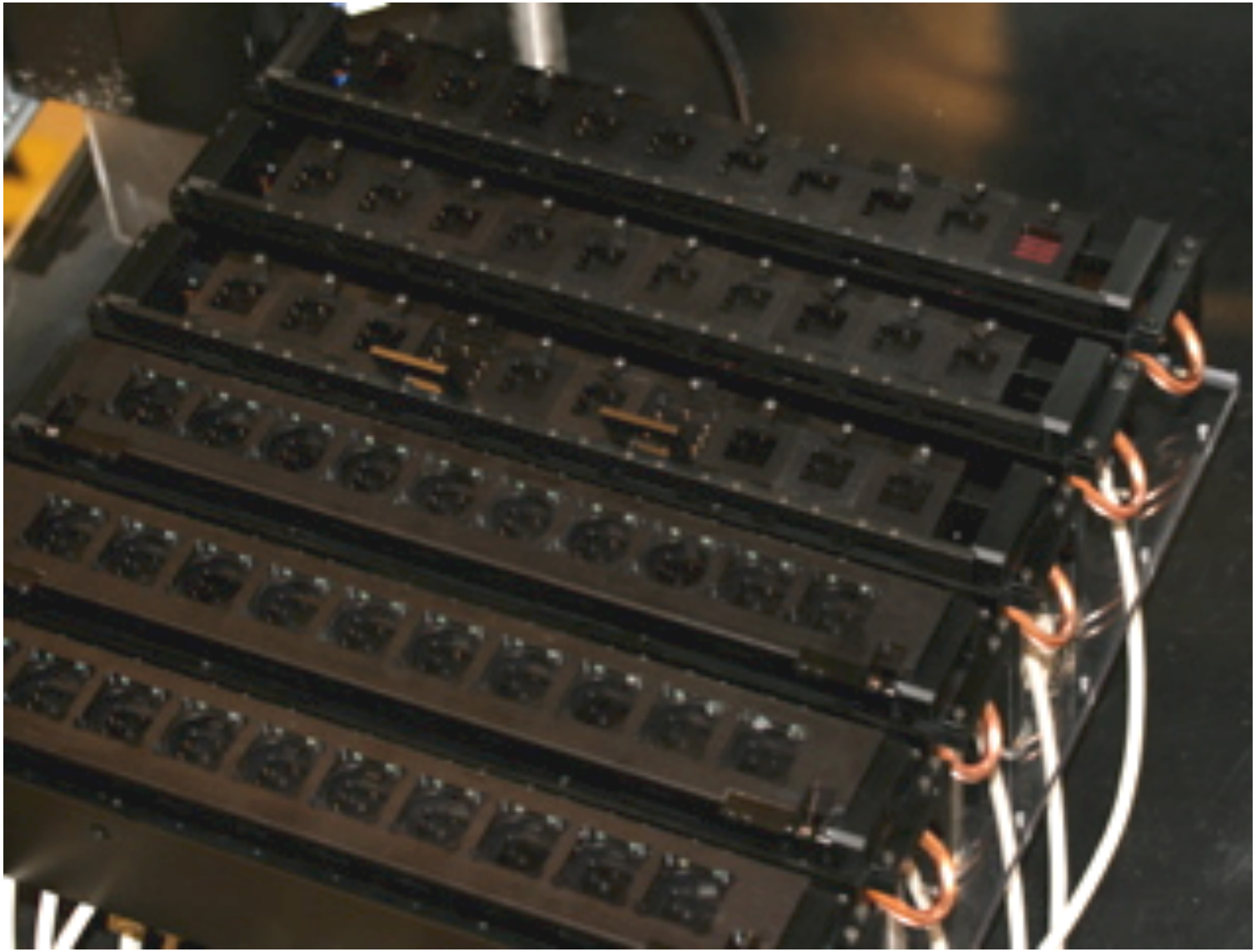
Modular multichannel *JV* reliability system

- 2 systems:
  - Ambient
  - Controlled atm. (glovebox)
- Up to 360 devices (60 substrates) per system
- Retractable shutters with 1” square cutouts → fully settable illumination conditions (ND & color filters, constant/shuttered illumination)
- Up to six temp. (0-85C)

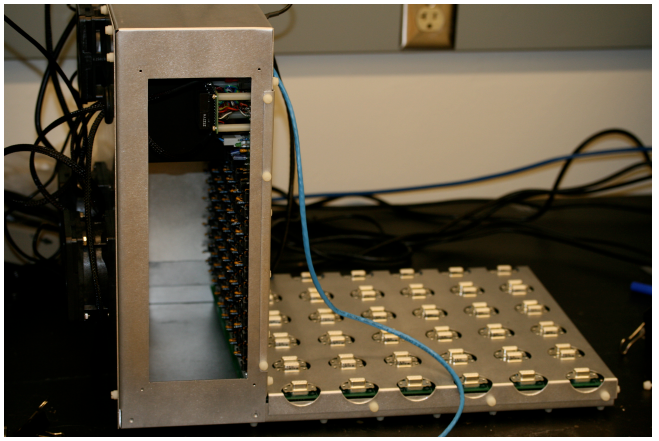




Combinatorial Degradation Setup

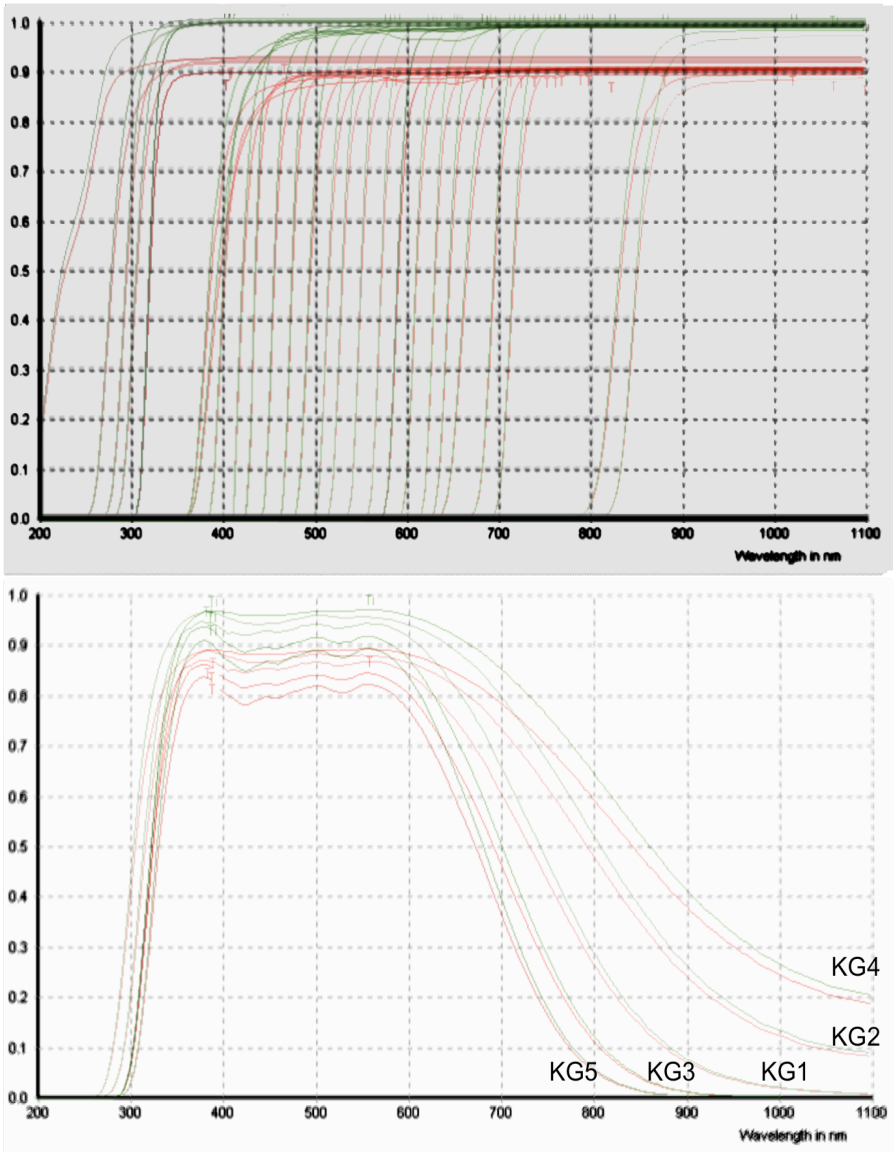


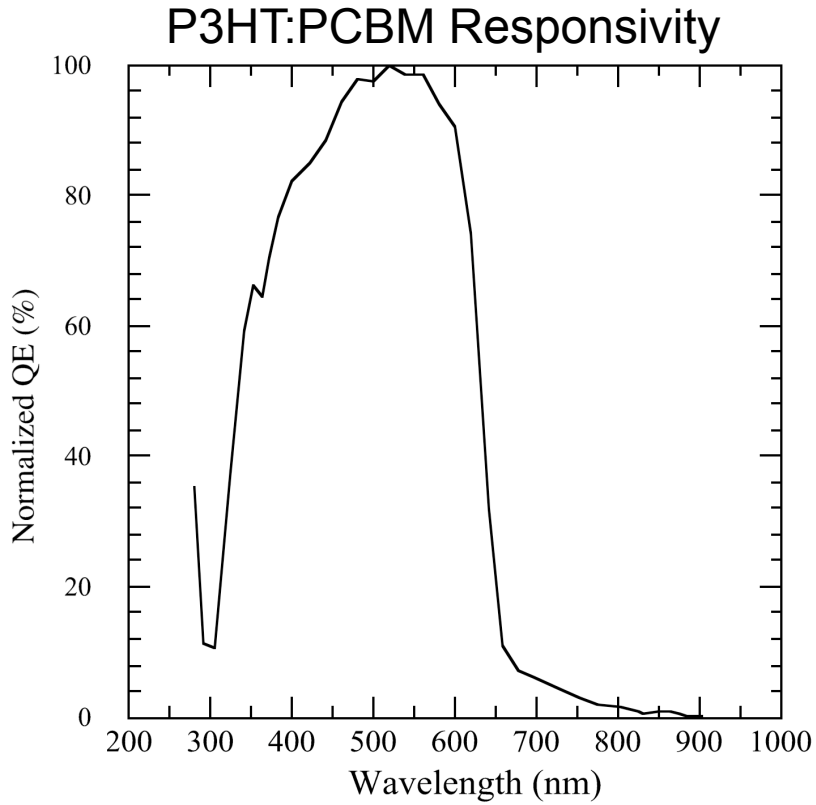
Measurement Electronics



- Six banks
- Settable load conditions
- 60 simultaneous *JV* curves
  - ± 6 μA resolution (100 mA range)
  - ± 1 μA resolution (10 mA range)
- ± 10V output (0.15 mV resolution)
- Reference diode monitoring (two/bank)
- Temperature monitoring (two/bank)

Color Filter Selection





Standing Questions

- Wavelength dependence
- Intensity dependence
- Temperature dependence
- Load conditions
- Healing factors from cycled illumination
- Interfacial vs active layer degradation
- Material system (is each OPV material system as different as each inorganic system?)
- What are acceptable statistics?

OPV Effort at NREL

National Center for Photovoltaics

Dr. Teresa Barnes
Dr. Jeremy Bergeson
Dr. Joseph Berry
Dr. David Ginley
Dr. Dana Olson
Dr. Zybyzlaw Owczarcyk
Dr. Matthew Reese
Dr. Benjamin Rupert

Chemical & Biosciences Center

Dr. Andrew Ferguson
Dr. Brian Gregg
Dr. Nikos Kopidakis
Dr. Jao Van de Lagemaat
Dr. Ziqi Liang
Dr. Matthew Rawls
Dr. Thomas Reilly
Dr. Garry Rumbles
Dr. Michael Woodhouse

Materials & Computation Sciences Center

Dr. Jeffrey Blackburn
Dr. Peter Graf
Dr. Kwiseon Kim
Dr. M. Erkan Kose
Dr. Robert Tenent

Graduate Students

Jamie Albin
Brian Appleby
Allison Kanarr
Anthony Morfa
Will Rance
K. Xerxes Steirer
Matthew White
N. Edwin Widjonarko

Affiliates

Prof. Reuben Collins (Mines)
Prof. Sean Shaheen (Univ. of Denver)
Dr. Alexandre Nardes (Univ. of Denver)